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MEASURING OPERATIONAL DEFLECTION SHAPES WITH A SCANNING P-U PROBE

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Scanning measurement techniques allow reducing significantly the number of sensors required to characterize time-stationary sound fields. Therefore, it is possible to produce sound maps by combining the signal acquired while moving a transducer with its tracking information. Structural vibrations can be measured acoustically by using a particle velocity sensor or Microflown since particle velocity is proportional to surface displacement under specific conditions. Moreover, relative phase information can be acquired by adding an additional static reference sensor. Combining particle velocity with relative phase information across the structure gives a very powerful visualization technique for studying operational deflection shapes (ODS). In this paper a theoretical basis of the measurement principle is presented along with a experimental example. In addition, a discussion focused on the advantages and disadvantages of the particle velocity based scanning method is given.

1. Introduction

Understanding the dynamic behavior of a component, machine or structure is a key factor for controlling noise, vibration, fatigue or wear problems. Conventionally, analytical modal analysis is used to characterize resonant vibration in machinery and structures from a theoretical point of view. However, it is often required to study a structure under one or few specific conditions. For particular scenarios it has been proven that direct measurements are faster, simpler and more accurate than analytical predictions [1]. Experimental modal analysis can be performed by measuring Operational Deflection Shapes (ODSs), and then interpreting or post processing them in a specific manner to define mode shapes [2, 3].

The most widespread techniques for testing Operational Deflection Shapes are based on step-by-step or simultaneous measurements with accelerometers. Nonetheless, attaching transducers directly to a vibrating surface structure may not be always possible. This fact has increased the popularity of non-contact solutions based on measurements with Laser Doppler Vibrometers (LDV) [4]. LDV systems allow the fast acquisition of a high number of measurements with a good spatial resolution but their noise floor is conventionally higher than most accelerometers, specially at higher frequencies. The high price and setup complexity of current commercial systems limites the use of LDV for most common applications.

Alternatively, acoustic particle velocity sensors or Microflowns [5, 6] have been proven to be suitable for measuring non-contact vibrations [7–11]. In the latter, it has become possible to use the Microflown in the areas of experimental modal analysis (EMA) and operational modal analysis

(OMA) thanks to the so-called Very Near Field (VNF) assumption. It states that in the region really close to a vibrating surface, the air particle velocity measured by the Microflown in that point where the probe is positioned equals the velocity of the corresponding point on the surface. The structure-borne noise produced by the vibration is measured by the probe, in terms of sound pressure and particle velocity. Next, this information can be effectively utilized as a direct measurement of the vibration itself under certain boundary conditions (see Section 2.1).

Several studies have revealed the potential of using P-U probes for measuring structural vibrations with step-by-step techniques but so far there is no evidence about the viability of measuring ODSs using P-U probes with scanning methods, such as "Scan & Paint" [12–14]. Scanning measurement techniques allow reducing significantly the number of sensors, time and cost of the experiments but they are constrained to assess time-stationary sound fields. Therefore, scanning ODSs measurements could be suitable for charactering structures excited with time stationary forces.

This paper aims to explore the use of a scanning P-U probe for measuring Operational Deflection Shapes of a stationary vibrating structure. To that end, an aluminium panel was excited by wall pressure fluctuations generated by the interaction of a moving flow with a half cylinder placed upstream. The flow speed was constant during the experiment so the excitation can be defined as stationary in time. In the following sections a theoretical base of the problem is given along with experimental data which support the validity of the measurement technique proposed.

2. Background Theory

Two fundamental aspects are covered in this section: the capability of the Microflown particle velocity sensor for performing non-contact vibration measurements and the importance of measuring Operation Deflection Shapes for vibroacoustic applications.

2.1 Microflown sensor for vibroacoustic applications

The following derivation follows [7], [8]. Let us start by defining the Helmholtz wave equation in terms of velocity potential $\Phi(r)$, i.e.

$$\bigtriangledown^2\Phi + k^2\Phi = 0 \tag{1}$$

where $\bigtriangledown^2$ is equivalent to the Laplace operator and k is the wave number ($2\pi f/c_0$). To describe the sound field of a vibrating surface Equation (1) should be solved considering the following boundary conditions:

$$\begin{cases} u_n = \partial\Phi/\partial_n, & \text{if } r = 0 \\ \\ \Phi \propto e^{jkr}/r, & \text{if } r \rightarrow \infty \end{cases} \tag{2}$$

where r is the distance to the vibrating surface; ∂/∂_n is the normal derivative and u_n is the normal component of the particle velocity. The observable acoustic values, sound pressure p and particle velocity $\mathbf{u}$, are connected with the potential such as

$$\mathbf{u} = \bigtriangledown\Phi \quad , \quad p = -j\omega\rho_0\Phi \tag{3}$$

where $\bigtriangledown$ represents gradient operator and ρ_0 is the density of the medium (air). According to [7] it is possible to establish a region between the vibrating surface and the beginning to the conventionally called 'Near Field' where Equation (1) is reduced to the Laplace equation for incompressible fluids. In order to derive this expression it is necessary to perform a Taylor series expansion of the velocity potential term $\Phi(r)$ in the neighborhoods of the surface and then consider only sound waves of wavelength (λ) much greater than the spatial wavelength which defines the vibrating surface (L). In summary, it is shown that the sound field at a normal distance r from a vibrating surface is called the very near field if the following two conditions are met:

$$\begin{cases} r << L/2\pi, & \text{condition (I)} \\ \\ \lambda >> L, & \text{condition (II)} \end{cases} \tag{4}$$

In the very near field the normal component of the particle velocity coincides with the structural velocity of the vibrating surface with neglectable error. Previous measurements have shown that condition (I) of Equation(4) is not very strict, the surface velocity profile can still be determined at a distance of $L/2$.

These considerations are the basis of vibration measurements for Microflown P-U probes. An important issue is related to the estimation of the very near field size along the normal direction to the surface. To be this condition verified, r has actually to be at least two orders of magnitude smaller than $L/2\pi$. Nevertheless, it must be highlighted that the effective wavelength associated with the vibrating surface will change with frequency according to the mode index. For a simple geometry, such as a rectangular panel of dimensions L_x and L_y, L can be defined as

$$L = \sqrt{\left(\frac{L_x}{n_x}\right)^2 + \left(\frac{L_y}{n_y}\right)^2} \tag{5}$$

where n_x and n_y are the mode index for the x and y axis, respectively. This means that as we go up in frequency the measurement distance range that allow us to measure direct structural vibrations using a PU probe is reduced according to the panel size and the mode index.

2.2 Operational Deflection Shapes

Operational Deflection Shapes (ODSs) are representations of relative information across space. They provide very useful results for understanding and studying the absolute dynamic behavior of a component, machine or structure. Human understanding in mainly based on seeing hence the visualization of the vibration behavior by ODSs may lead to discover which optimal modifications should be made in order to control noise and vibrations, lessen fatigue, reduce wear or solve related problems [1]. Modification decisions can be supported by one or a few frequency response measurements to check for the existence of resonance conditions at the critical points discovered with the ODSs.

Operational Deflection Shapes can also be predicted from analytical models (modal analysis) by defining the boundary conditions and operating forces if these terms are measurable in the assessed scenario. If, however, the objective is to study a particular structure under one or a few specific conditions, a direct ODS measurement is faster, simpler, and more accurate than analytical predictions [1]. No errors are introduced derived from geometric problems, wrong boundaries conditions or linearity issues.

To understand the physical meaning of an ODS, they could be seen as the picture which would be obtained if an stroboscope were used to freeze a vibrating object at a desired frequency. Hence, an ODS is an observation, or visualization, of particular dynamic behavior but which does not give the characteristic dynamic properties of a particular structure.

An ODS can be defined from any forced motion, either at a moment in time, or at a specific frequency. Conventionally, ODS are computed from a set of sampled time domain responses acquired simultaneously or using pairs of frequency domain data sets. An overview of the most widespread ODS measurement methods in time and frequency domain is given in [15]. In our case, the use of only one probe along with a fixed sensor lead to deal directly with frequency domain techniques.

Several frequency domain techniques could be implemented, but the use of PU probes have been very suitable for computing ODS FRF measurements which does not use information about the excitation forces.

The measurement procedure is similar to the procedure used for single input modal analysis but instead of using the excitation force as reference, ODS FRF requires the use of a fixed reference sensor along with other transducer which evaluate different regions in the space. Each ODS FRF is formed by replacing the magnitude of each cross-spectra between the moving and static sensor with the auto-spectra of the scanning transducer. The phase of the cross-spectra is preserved as the phase of the ODS FRF. The obtained new term will contain the correct magnitude of the response at each point across the vibration surface, and the correct phase relative to the fixed reference position. Evaluating a set of ODS FRF measurements at any frequency yields the frequency domain ODS for that frequency. Some examples of ODS FRF measurements are given later on in Section 6.

At or near one resonance peak, the ODS is dominated by a mode. Therefore, the ODS is approximately equal to the mode shape of the vibrating structure evaluated. In addition, modal parameters (natural frequency, damping, & mode shape) can be obtained from a set of FRF measurements. These characteristic properties are obtained by post-processing a set of ODS data. Consequently, a set of FRFs can be thought of as a set of ODSs over a frequency range [15]. A good representation of the model shapes using operational deflectiong shapes can be achieved using a random excitation source as the turbulence generated by flow-solid interaction.

3. Measurement methodology

If the measured signals can be assumed time stationary, continuous scanning measurements can be then performed for characterizing the Operational Deflection Shapes in a fast and efficient way. Recent works have introduced a novel scanning method called "Scan & Paint" [12–14] for measuring sound pressure, particle velocity, intensity, sound absorption and acoustic impedance. The properties of the sound field are determined and visualized via the following routine: while the probe is moved slowly over the surface, pressure and velocity are recorded and, at the same time, a video image is captured. Next, all data is processed. At each time interval, the video image is used to determine the location of the sensor. The absolute position of the probe is unknown, only the 2D coordinates relative to the background image are computed. Then, an acoustic color plot is generated.

Recent developments have introduced a new way of acquiring phase information across the sound field with scanning techniques by using an additional fixed sensor [16]. This allows applying advanced techniques such as transfer path analysis or adaptive beamforming by taking into account the phase relation between fixed and moving transducers.

4. Experimental Setup

The experiments carried out simulate the flow induced vibration and noise radiation from a side car window due to the turbulent wake produced by the wing mirror. The turbulence generated are convected downstream causing surface pressure fluctuations on the side car window that produce its vibration and the consequent noise generation. This excitation, despites its random nature, can be defined as stationary in time if the flow speed is fixed. Therefore, the car window is exposed to a broadband excitation stationary in time. The measurements were done in the subsonic open jet anechoic wind tunnel located at the Institute of Sound and Vibration Research (ISVR) where a very low noise and low turbulent flow of up to 150 km/h can be achieved. For these experiments, a flow with constant speed of 144 km/h was generated.

Instead of using a real car window, an equivalent panel with similar dynamic properties was used. The reason for this change is that the use of a real car window presents additional complications for the experiment set-up as for example the difficulty to drill it in order to attach it to the framework used. Evaluating the dispersion curves and coincidence frequency of a standard glass car window 4 mm thick and panels of different materials it was found that an aluminum panel 4 mm thick provide very similar performance. The aluminium plate was fixed in position by screwing them to a frame so as to approximate an idealised zero displacement boundary condition at the edges.

An acoustic baffle was used to surround the test panel in order to minimised the noise generated by flow interaction with the edges of the panel and the diffraction of sound around it. In order to avoid the transmission of vibration between panel and baffle they were not directly connected and whereas the acoustic baffle was supported by stands clamped to the floor of the chamber to stabilize the whole set-up, the frame where the aluminium panel was attached was suported by different stands.The remaining cavity between the edges of the panel and the baffle was carefully filled with dense foam lined barrier material avoiding noise transmission through any leackeages.The acoustic baffle was built from a 15 mm thick MDF board and covered with a dense acoustic foam on the flow-facing side, this isolated the baffle from both the acoustic field generated by the vortex shedding from the mirror and the turbulence in the flow. The rear panel of the baffle was covered by pieces of foam trying to reduce noise radiation from the baffle, thus improving the signal to noise ratio of the particle velocity measured by the P-U Probe.

The wing mirror was substituted by a half cylinder that has simpler geommetry. It was placed on the plate just before the upstream edge of the aluminium panel and its centre was aligned with the symmetry axis of the aluminium panel in the stream wise direction and also aligned with the centre of the noozle in order to ensure the half cylinder was located inside the core of the jet.

Figure 1 shows a front and rear view of the experiment set-up where all the details explained above can be seen.

Figure 1. Front (left) and rear view (right) of the experiment set-up

5. Validation of the methodology

Step-by-step measurements have been performed placing an accelerometer at several positions across the vibrating structure. Then, a P-U probe have been sweep very close to the surface (less than 5 centimeters). By discretizing the scanning measurement through the space according to the Scan & Paint "grid method" it has been possible to compare directly surface velocity measured with the accelerometer and with the scanning P-U probe. Figure 2 presents the measurement results for two different positions.

As can be seen in Figure 2 results match with remarkable accuracy in the band from 90 Hz to 500 Hz. However, there is an overestimation of the structural vibration at very low frequencies due to the poor signal to noise ratio in the presence of high speed flow leaked from the front side of the

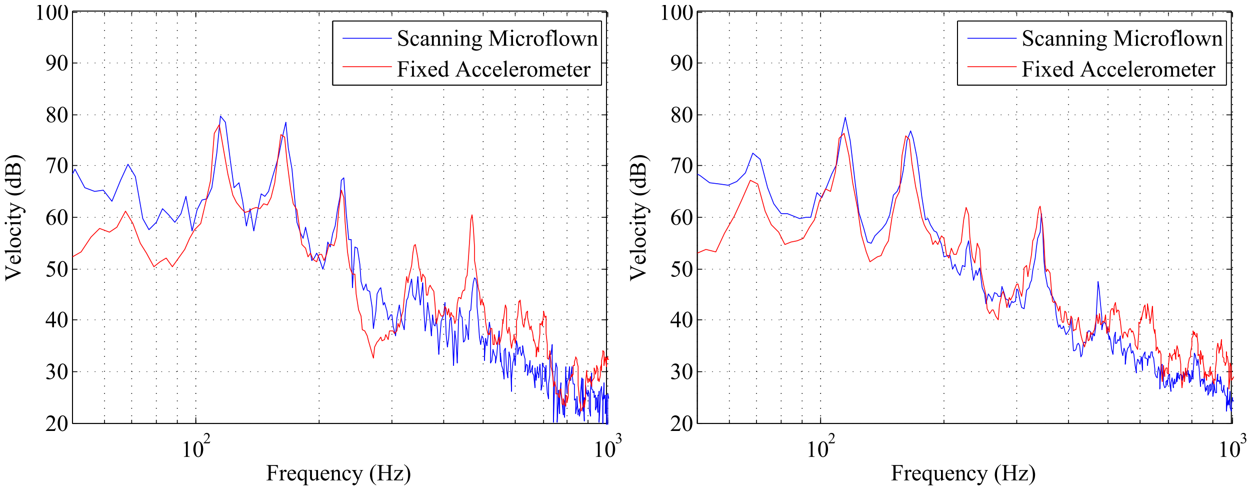

Figure 2. Comparison of surface particle velocity at two different positions

panel. In addition, it is important to highlight that the higher assessable frequency will depend on the spatial wavelength L associated with the vibrating panel and the measurement distance between panel and transducer. The measurement boundaries can be estimated according to the theory given in Section 2.1. For the case studied 500 Hz has be found the highest assessable frequency for the scanning measurements performed.

6. Experimental results

As have been pointed out in Section 2.2, Operational Deflection Shapes (ODSs) allow us to study the dynamic behaviour of a structure or a vibrating plate across the entire spectra. Nonetheless, it is more interesting to focus only where the evaluated element present the operational resonances. At certain specific frequencies, which conventionally are very close to the natural modes of the structure, the input energy is highly amplified.

Figure 3 shows the ODSs at the first four resonant frequencies which clearly coincide with the horizontal natural modes of the vibrating panel. Particle velocity plots are presented with relative phase information referred to a fixed accelerometer attach to the surface (ODS FRF). These results show very clear ODSs of the structure, supporting the potential of using scanning P-U intensity probes for vibroacoustics applications.

7. Step-by-step versus scanning measurements

One of the main problems of conventional techniques is the time required to perform the measurements and post process the data. However, manual sweeps of a single probe are a much faster procedure for directly obtaining the information required. Current "Scan & Paint" methodology requires only few minutes for carrying out a high spatial resolution characterization of any panel size.

Not only the measurement protocol but also the post processing stage is fairly intuitive. The use of a video camera make sure that almost all areas are captured and the measurements are filmed which proved to be helpful with trouble shooting. Color maps overlaid on pictures give a direct feedback that is easy to understand.

The ability of resizing the measurement grid in a post-processing stage allows to creat the high spatial and frequency resolution results that could only be compared with step-by-step measurements which are vastly more time consuming.

The main outcome of a measurement technique is to be able to ensure accuracy. The low error presented in the comparison between scanning P-U probe and accelerometer demonstrate the great

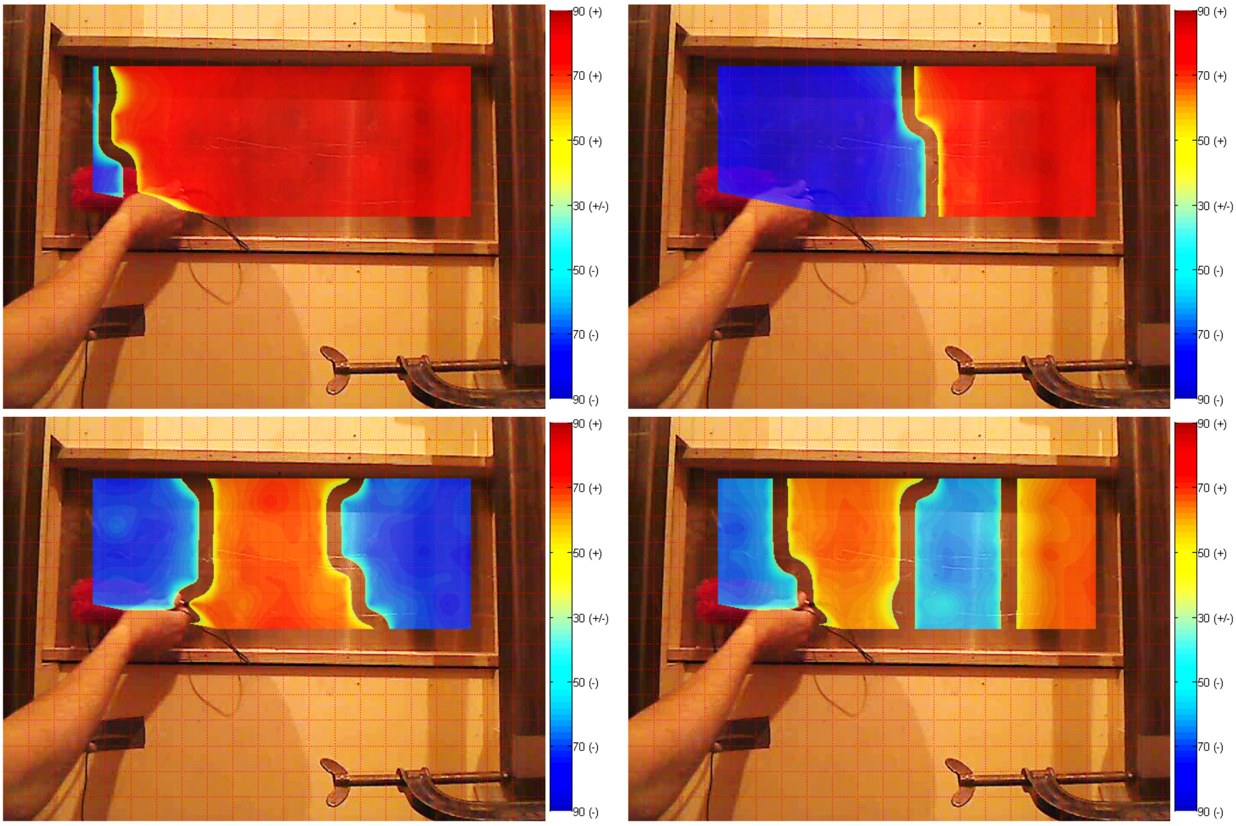

Figure 3. Operational deflection shapes at 115 Hz (top left), 165 Hz (top right), 230 Hz (bottom left), 342 Hz (bottom right)

potential of combining velocity-based scanning techniques for vibroacoustic applications. Fixed point measurements suffer from discretization errors, choosing a fixed position to measure is always a risk which could derive in spatial aliasing and resolution limitations.

One of the main problems of conventional scanning techniques is that time stationary conditions are required. Although some industrial applications can only be tested using transient or impulsive excitations, many problems can be solved using a time-stationary regime.

Human errors such as touching the surface or producing noise while the probe is moving are inherent to the measurement technique. Nevertheless, they can be detected and avoided during the post processing stage.

Because the method does not measure the absolute probe position, there is only 2D information related to the background image which could lead to position errors during the scanning. Therefore, if the distance between the scanning P-U probe and the vibrating panel changing during the measurement this could not be taken into account. Nonetheless, a cross-laser could be used for introducing a visual reference which helps to move across the evaluated measurement plane.

8. Acknolegments

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9. Conclusions

The use of a scanning P-U probe for measuring Operational Deflection Shapes of a stationary vibrating structure have been investigated. Theoretical limitations of the problem have been presented along with experimental data which support the validity of the measurement technique proposed. Results present the most relevant ODSs of the structure in a clear way, supporting the potential of using scanning P-U intensity probes for vibroacoustics applications.

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